Ad Hoc Networks 11 (2013) 1421–1431

Contents lists available at SciVerse ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

EFCon: Energy flow control for sustainable wireless sensor networks

Xingfa Shen [a,*], Cheng Bo [a], Jianhui Zhang [a], Shaojie Tang [b], Xufei Mao [b], Guojun Dai [a]

[a] Institute of Computer Application Technology, Hangzhou Dianzi University, Hangzhou 310018, China
[b] Department of Computer Science, Illinois Institute of Technology, Chicago, IL 60616, United States

ARTICLE INFO

Article history:
Available online 23 July 2011

Keywords:
Wireless sensor networks
Sustainable
Energy flow control
Solar
Energy utilization

ABSTRACT

The rapid advances in processor, memory, and radio technology enable the development of small, inexpensive sensor nodes that are capable of sensing, computation, and communication. However, the severe energy constraints of the sensors present major challenges for long-term applications. In order to achieve sustainability, environmental energy harvesting has been demonstrated as a promising approach. In this work, the energy utilization scheme is investigated for wireless sensor networks with energy harvesting nodes. The energy utilization system is divided to three parts: *energy harvesting*, *energy consuming* and *energy storage*. Then the sustainability problem is formulated as an energy flow control problem. An energy flow control system, called EFCon, is proposed to keep the balance between energy supplies and demands. EFCon consists of two phases, *energy flow direction control* and *flow rate control*. In the phase of energy flow direction control, the system dynamically switches among four patterns: *flood flow*, *direct flow*, *compensate flow*, and *backup flow*, according to current environmental energy condition and the residual energy condition. Once the energy flow direction is determined, a corresponding energy flow rate control strategy will be adopted for efficient energy utilization. The EFCon is implemented and validated by a long-term deployment in real testbeds. The experimental results indicate that the EFCon outperforms existing designs.

1. Introduction

The rapid development in micro-electronics and sensor technology has promoted the wireless sensor networks (WSNs) to be a promising technology for environment monitoring, military surveillance and scientific research. WSNs consist of hundreds of working nodes deployed in a large-scale field to collect, process and transmit useful information to remote base station for further study.

We have deployed the GreenOrbs system (http://www.greenorbs.org) [1], one of largest sensor networks in the world, to collect various sensory data including temperature, humidity, illumination, and carbon dioxide from a forest. One of our objectives is to maintain the sustainability of the network for at least 1 year, which is also demonstrated to be necessary for other applications of sensor networks. In GreenOrbs, hundreds of sensor nodes, each powered by a pair of rechargeable NiMH AA batteries, are deployed in the forest. The load varies over a large range, microwatts in standby and milliwatts when active [2], thus a sensor node equipped with two AA batteries can only survive a few days in 100% duty cycle. Therefore, harvesting energy from the environment has been widely recognized as a promising approach to ensure the sustainability of the network.

From the perspective of energy utilization, the energy supplying system of WSNs consists of three parts, as shown in Fig. 1, the energy harvesting device, energy consuming device and the energy storage device. The thick black arrow in Fig. 1 stands for the direction of energy flows, where the thickness degree of arrow indicates the rate of energy flow.

---

* Corresponding author.
E-mail address: shenxf@hdu.edu.cn (X. Shen).

1570-8705/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.adhoc.2011.07.003

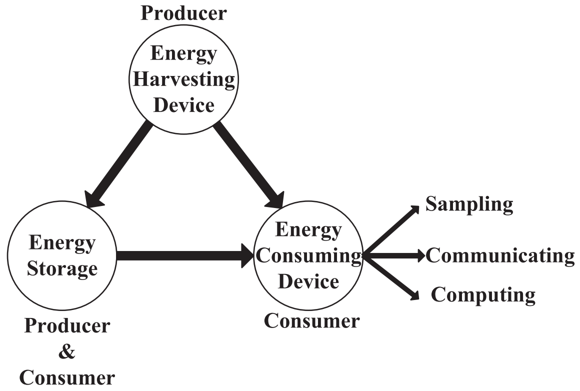


Fig. 1. Energy utilization in WSNs.

- The role of energy harvesting device is to harvest environmental energy to power the sensor node, which is similar to the producer in macroeconomics.
- The energy consuming device utilizes the harvested energy to support various work loads, such as sampling, communication, and computing. It is similar to the consumer in macroeconomics.
- The energy storage device is used to store energy, harvested from environment, and it provides power to the external sensor node. It plays the role of either the producer or consumer in different conditions.

In order to achieve the sustainability, an energy flow control system is required to keep the residual energy in the battery above a certain threshold. The energy flow control system is analogical to a water conservation system. The energy storage can be considered as a water tank, which collects water from upper reaches of the river and raining, and meanwhile supplies water for drinking, generating electricity, irrigation, etc.

There are three major challenges in the energy flow control system:

- It is difficult to precisely predict the harvested energy.
- The energy utilization pattern is relatively complicated and application-specific.
- Different energy storage devices have their own characteristics, for instance, the ultra-capacitor suffers from energy leakage while the Li-ion battery has shut-down voltage to prevent the battery from over-discharging.

In this work, we mainly address the problem of how to handle these challenges mentioned above and achieve balance between energy harvesting and consuming. We formulate the problem as an energy flow control problem. Essentially, the goal is to keep the residual energy level in the energy storage of the node above a certain threshold in case of urgent events, for example, making a sentry node be able to send out its last warning before dying.

For the purpose of controlling the energy flow in WSNs, we design a novel solar powered energy utilization system named EFCon. The solar [2] panel, the Li-ion battery, and TelosB [3] node are used as the energy harvesting device, the main battery, and the external sensor node, respectively.

The main contributions of this paper are as follows:

- We formulate this energy utilizing problem as an energy flow control problem.
- We design a method to control the directions of energy flow among the three parts of the energy supplying system for WSNs.
- We propose a novel dynamic adjusting algorithm of duty cycle, sampling rate or local data aggregation granularity to control the energy utilizing rate.

The rest of this paper is organized as follows. Related work is described in Section 2. Section 3 discusses the energy flow control problem we formulated. Section 4 gives the details of energy flow control system, EFCon. System implementation and evaluation are presented in Sections 5 and 6, respectively. Finally, Section 7 concludes the paper.

2. Related work

Aiming at the WSNs, researchers have designed several systems harvesting energy from human activity and environment, such as solar, wind [4], vibration [5], and thermal [6]. Compared to the sensor node powered by batteries only, the energy is no longer finite, and the quantity of data to be transmitted are not limited as well.

Solar powered WSN catches lots of researchers' attention in recent years because of its convenience, environment friendliness, and sustainability. Ting Zhu designed a leakage-aware energy synchronization system, called TwinStar [7], taking ultra-capacitor as the only energy storage. Regard of its high leakage, TwinStar controls the leakage at a stable level by introducing a feedback control technology. But the big volume and high cost make it an unperfect choice for long-term deployment. Besides, there are some other systems based on solar power, such as Trio [8], AmbiMax [4], PUMA [9], and Heliomote [10,11].

For single node with energy harvesting, there are few studies on energy management and scheduling. More attentions are paid to the miniaturization of solar power system and increase of the transformation rate between environmental and electrical energy. For instance, the Maximum Power Point Tracker (MPPT) [12], which is designed to regulate the load condition and make the solar panel work on its MPPT condition. However, in real cases, there are plenty of factors affecting the transformation rate that may degrade the performance of MPPT.

For the network with energy harvesting, there are many studies on network-scale energy management and scheduling with energy harvesting. Recently, Yang developed a reliable storage service, called SolarStore [13], that adaptively trades off storage reliability vs. energy consumption in solar-powered sensor networks. Uniform Sensing Protocol (USP) [14] is a protocol that makes the whole network monitor the environment on average throughout the entire lifetime. However they did not mention how to predict the diversification of environmental energy, nor the influence of duty cycle on the energy.

Considering that existing researches do not take energy flow into account, we first propose the EFCon system to manage the energy flow and thus maintain the sustainability of the network. The EFCon system is based on our previous hardware platform SolarMote [15], which is able to supply sustainable energy to sensor nodes in several real applications.

3. Problem formulation

In WSNs, energy utilization is considered to be a critical problem. To our best knowledge, there is few work on the balance between the energy generation and consumption for WSNs. We formulate the energy utilization problem as an energy flow control problem, which is illustrated in Fig. 2, and thus propose a novel energy flow control method named EFCon in Section 4.

3.1. System description

In our system, we adopt a well-recognized solution by introducing three components, the solar panel, the Li-ion battery, and the TelosB node. The functions of these components are as follows:

- Solar panel: harvests environmental energy, and transfers it to electric energy.
- Li-ion battery: saves and supplies electric energy.
- TelosB node: collects, measures, and processes useful information, including energy profile for further use.

Obviously, the energy flows through the solar panel, Li-ion battery, and TelosB node. There are four energy flow patterns according to different energy utilizing methods, as shown in Fig. 2.

- The solar panel provides the energy to both Li-ion battery and TelosB node (the green arrow marked with 1).[1]
- The solar panel solely provides the energy to TelosB node (the blue arrow marked with 2).
- Both the solar panel and the Li-ion battery provide energy to the TelosB node (the pink arrow marked with 3).
- The Li-ion battery solely provides energy to the TelosB node (the red arrow marked with 4).

The thickness of each arrow indicates different energy flow rate among components, and the energy flow rate can be controlled by an energy flow rate control algorithm, which is described in detail later.

3.2. Challenges

3.2.1. Solar energy

Compared to other energy sources, such as wind, piezoelectricity, vibration and thermal, solar energy is demonstrated to be the most attractive energy source in the nature because of its high energy density and low fabrication cost. However, the solar panel cannot supply stable energy because of the variation of weather, location and time. Besides, the energy harvested by solar panel is usually unpredictable. Fig. 3a plots the energy harvested by two solar panels in two different locations in 1 day. It is obvious that these two energy harvesting patterns are significantly different from each other. As shown in Fig. 3a, weather plays an important role in a solar-powered system. Taking the solar panel A for example, with the direct sunlight, the generated current increases in the morning, and reaches the peak at noon. In the afternoon, the current declines with a slight fluctuation because of the cloudy weather. In addition, the energy gain is not in complete accordance with the luminous intensity. As shown in Fig. 3b, the luminous intensity remains stable (around 1400) throughout the daytime, and drops to 0 suddenly after sunset.

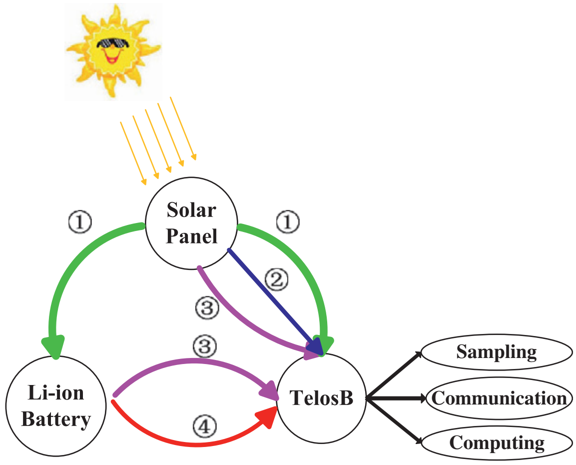


Fig. 2. Energy flow pattern.

3.2.2. Energy storage characteristics

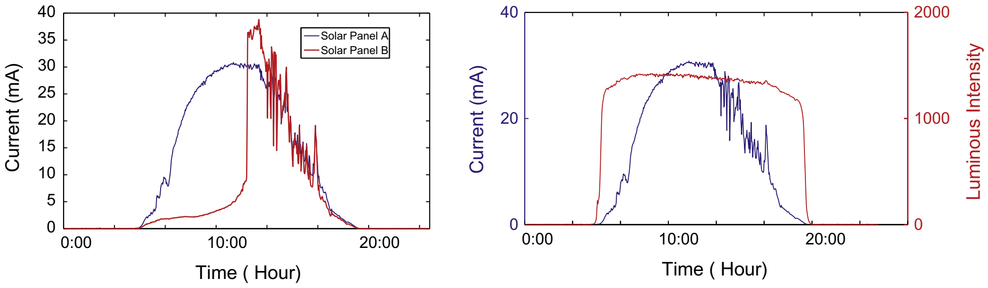
To store the harvested energy, researchers have proposed to use rechargeable batteries, e.g. NiCAD, NiMH, or Li-ion [11,12]. However, the common drawback of these batteries is the limited capacity.

In this paper, we choose Li-ion battery as the main battery due to the following reasons: (1) it can be formed into various shapes and sizes to fit the different devices; (2) it is lighter than other energy storage with equal energy space, such as ultra-capacitor; (3) the high open circuit voltage can be obtained in comparison to other rechargeable batteries, such as NiCAD and NiMH; (4) it does not suffer from memory effect and has a extremely low self-discharge rate of approximately 0.1% per month, compared with over 30% per month for common NiMH batteries and 10% for NiCAD batteries; and (5) the Li-ion battery has a higher power density than other batteries.

However, the Li-ion batteries can be extremely dangerous if mistreated, such as overheated, over-charged and over-discharged. To reduce these risks, Li-ion batteries are usually equipped with a small protection circuit in order to shut down the battery when the battery is charged to 4.2 V (over-charge voltage) or discharged to 2.7 V (over-discharge voltage). Therefore, in normal use, the

---

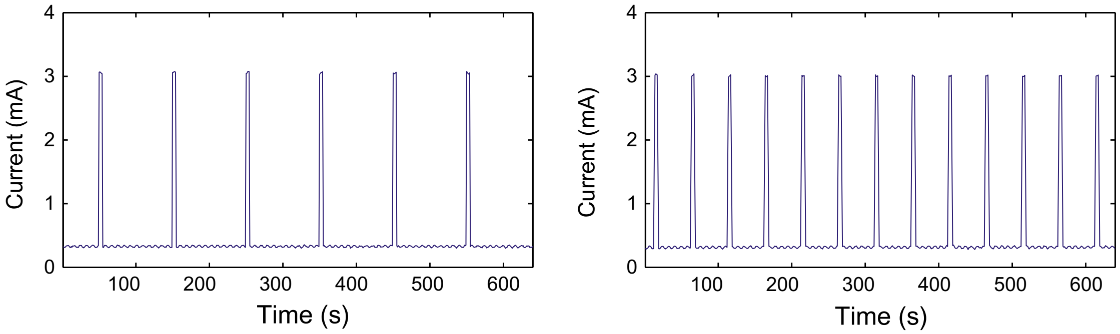
[1] For interpretation of color in Figs. 2–6, 9–13, the reader is referred to the web version of this article.



(a) Solar Energy Harvested by 2 Solar Panels over 24 Hours

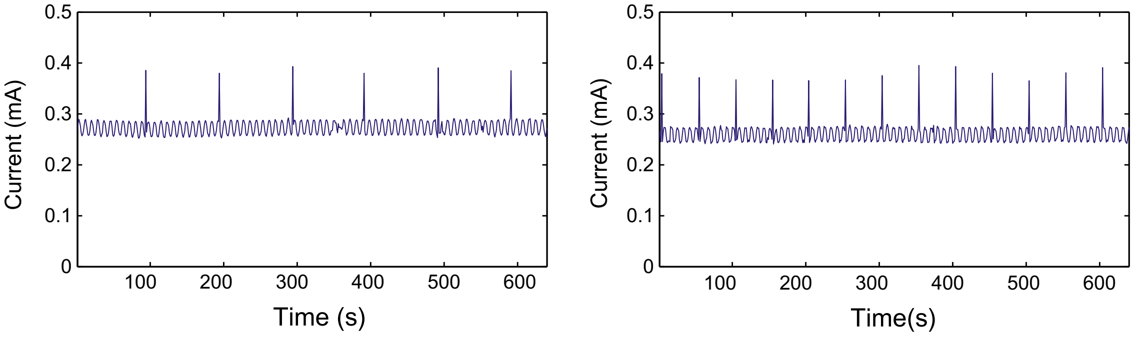
(b) Solar Energy vs. Luminous Intensity Pattern

Fig. 3. Environmental energy pattern.



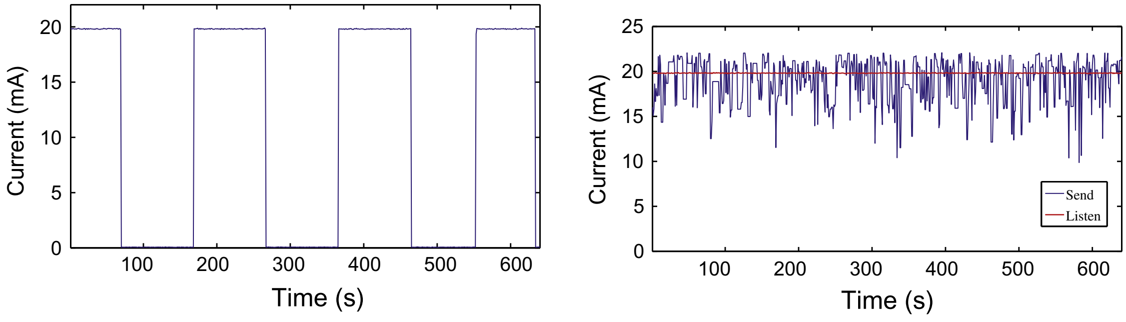
(a) 5% Duty Cycle with One LED On

(b) 10% Duty Cycle with One LED On



(c) 5% Duty Cycle with Light Sampling Once

(d) 10% Duty Cycle with Light Sampling Once



(e) 50% Duty Cycle with Idle Listening

(f) 100% Duty Cycle with Sending Packet vs. Idle Listening

Fig. 4. The impact of working loads on energy consumption.

battery is prevented from being deeply discharged. In a real energy flow control system, a threshold voltage should be established to make the sensor node alive and maintain the reliability of the whole network.

3.2.3. Sensor working load

Depending on the working load, the energy consumption mode of the sensor node is very complicated. In order to investigate the impact of different workloads on the energy consumption of each sensor node, we conducted a series of experiments, as shown in Fig. 4. We analyze different sets of active components (LED, Light Sampling, Idle Listening, and Sending Packet) and workloads (5%, 10%, 50% and 100%) by sampling the working current. Here, without loss of generality, we only choose four typical duty cycles of sensor node, i.e. 5%, 10%, 50% and 100%, to show the impact of different duty cycles on the energy cost.

As shown in Fig. 4, the duty cycle setting has a direct impact on the power consumption. In other words, the duty-cycled sensor nodes use less energy, due to the fact that the current is less than 0.3 mA when the sensor node is sleeping. The energy consumed by different active components is also different, among which the Sending Packet component depletes 2 mA more current than that of Idle Listening, about 22–20 mA. The Light Sampling component cost nearly 0.4 mA, the least among all components, and the LED costs only 3 mA.

3.3. Goal

Essentially, the ultimate goal of this work is to design a strategy to achieve the energy balance among solar panel, Li-ion battery and the TelosB node. To be specific, under the circumstance of limited energy storage, we propose a novel scheduling scheme ensuring a threshold of the residual energy, so that the sensor node can send essential messages before dying, thus keep the whole network sustainable.

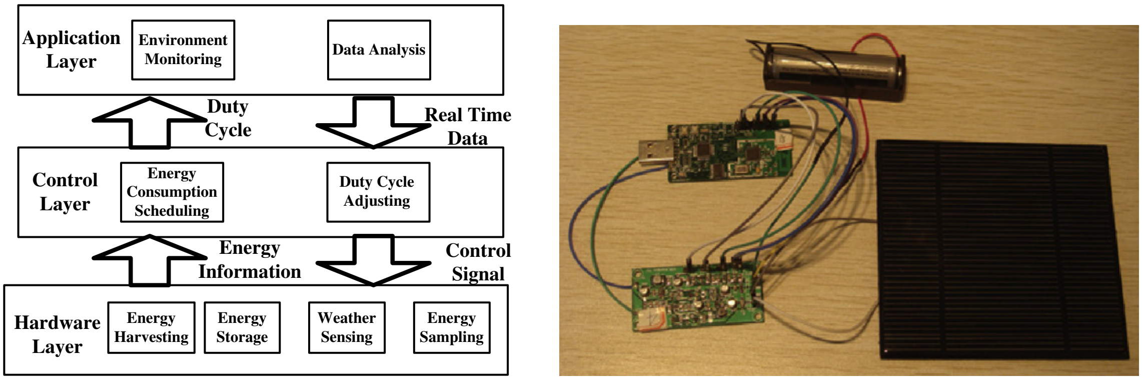
4. Energy flow control

The control of energy flow in WSNs is of great importance, analogical to the water controller in the water conservation system. The control process consists of two phases: (1) the flow direction control, and (2) the flow rate control. In the first phase, the flow direction is determined by the current condition of both environmental energy and energy storage. Once the flow direction is fixed, the process enters the second phase, where the flow rate will be adjusted accordingly.

4.1. Flow direction control

The flow direction control is used to dominate the direction of energy flow from one component to another. The flows have four patterns:

- *Flood Flow (FF)* pattern
  The *FF* pattern appears when the environment provide huge amount of energy resources to fill the energy storage tank and power the energy consuming device simultaneously. In other words, the solar panel harvests the solar energy to charge both the Li-ion battery and power the TelosB node.
- *Direct Flow (DF)* pattern
  The *DF* pattern is that the environment provides energy to the energy consuming device while the storage is standby. This mode always appears as the follow-up pattern of *FF*, when the environmental energy is sufficient and the energy storage is full. In this mode, the solar panel power the sensor node alone with the Li-ion battery standby.
- *Compensate Flow (CF)* pattern
  The most novel mode is the *CF* pattern, in which the weak energy harvested by the solar panel from the environment could not power the sensor node all alone. In order to fill the energy gap, the Li-ion battery supplies certain amount of energy. Under this circumstance, the utilization of environmental energy can be maximized.
- *Backup Flow (BF)* pattern
  The *BF* pattern means the energy storage supplies energy to the energy consumption device, i.e. the Li-ion battery powers the sensor node alone, when the environmental energy is not available, usually at night or in bad weather.



(a) System Architecture (b) EFCon Prototype

Fig. 5. Overview of EFCon system.

The transition among these four patterns is triggered automatically by the condition of the environmental energy supply that is closely related to external weather as well as the voltage condition of the internal energy storage device. As a key step of pattern transition, the changes of energy flow direction are controlled by an intelligent circuit board and the software on the TelosB node.

First of all, the sensor node samples the condition information including the luminous intensity, the environmental energy supply and the present residual energy of the Li-ion battery. The *FF* pattern will be activated if the environment energy is higher than that of Li-ion battery and the battery energy is not full. After the battery is charged to its full capacity, the *DF* pattern is triggered. If the environmental energy cannot support the work of sensor node alone, the *CF* pattern will be activated. And if the environmental energy is extremely low, the *BF* pattern will be triggered. Algorithm 1 describes the procedure of the pattern transition.

Algorithm 1. Transition procedure of energy flow patterns

```
Input: Environmental energy supplying level: $E_{En}$,
    residual energy level of Li-ion Battery: $E_{Li}$, luminous
    intensity: $L_{Luminous}$
Output: Pattern of energy flow
while True do
    Delay $T_{Delay}$;
    Sample $E_{Li}$ and $E_{En}$;
    if $E_{En} > E_{Li} \&\& E_{Li} < E_{Full}$ then
        Pattern: Flood flow;
    if $E_{Li} \geqslant E_{Full}$ then
        Pattern: Direct flow;
    if $E_{En} \leqslant E_{LBound} \&\& L_{Luminous} \leqslant L_{LBound}$ then
        Pattern: Backup Flow;
    else
        Pattern: Compensate flow
```

4.2. Flow rate control

The target of solar powered system is to make sensor networks sustainable. Existing solutions mainly focus on adjusting the duty cycle or sampling rate of the sensor node.

In EFCon, the energy flow rate is controlled based on the workload and the flow direction. Let W_{Basic} denote the working load of basic task the sensor node should do and $W_{Suggest}$ denote an addition small working load suggested by the application. In *FF* pattern, the sensor node works on $W_{Basic} + W_{Suggest}$ until the battery reaches the full. Then the *DF* pattern is triggered, and the sensor node works on a maximum working load, W_{Max}, according to the environmental energy condition. In order to keep the sustainability, in both *BF* and *CF* pattern, the sensor node works on its W_{Basic} mode to accomplish the basic tasks while saving energy as much as possible.

In the water conservation system, the flow rate of water is determined by the real purpose, such as drinking, irrigation, and generating electricity. Similarly, the energy flow rate in WSNs is determined by their applications. As to our best knowledge, the main methods of controlling energy flow rate are (1) duty cycle, (2) sampling rate, and (3) data aggregation. The method will be chosen according to the real application.

5. System implementation

Solar cell generates the most energy when fully illuminated, and light levels under typical shrubs are typically five percent or less of bright sunlight [16]. In addition, the weather also plays an important role in solar powered system. In the east costal regions of China, the weather chops and changes dramatically, thus the solar panel cannot generate sufficient electricity. Therefore how to extract the limited energy even under bad weather becomes a challenge. If we can make full use of those potential energy, and set the battery as a compensational power, the remaining energy in the Li-ion battery will be maximized at the end of each day.

5.1. System description

The uncontrollability and unpredictability of environmental energy is a critical obstacle for a sustainable sensor network. Therefore we propose a three-layer design of EFCon as shown in Fig. 5a, and a prototype of EFCon is shown in Fig. 5b.

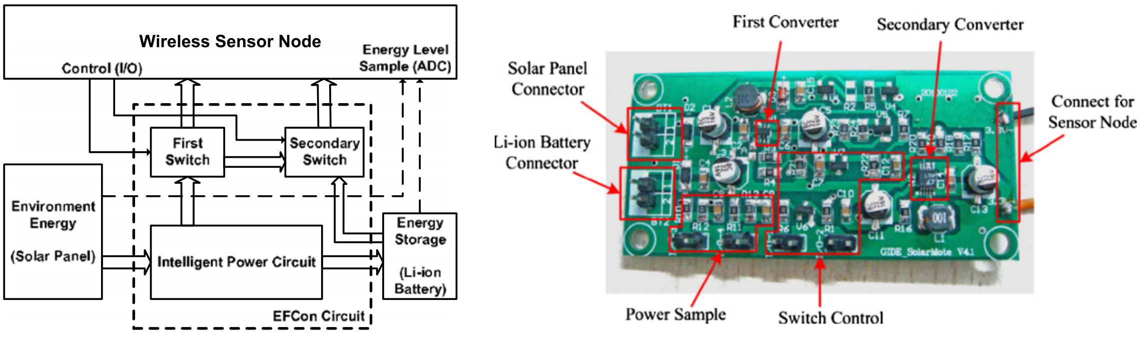
The hardware layer harvests the environmental energy by the energy harvesting circuit, and uses the Li-ion battery as the unique energy storage device to power the external TelosB node. The key component in the hardware layer is an intelligent circuit, whose functions include (1) monitoring the weather condition by coordinating with the Telosb node, (2) sampling the current residual energy of Li-ion battery as well as the current harvesting energy, and (3) controlling the energy flows among the different components.

The control layer executes the energy utilization strategy based on the current condition of Li-ion battery and the environment. There are two main conditions the control layer would face, energy-rich case and energy-poor case. In the energy-rich case, the control layer straightly triggers the signal to change the current direction to the secondary voltage stabilizer and charging circuit simultaneously. In the energy-poor case, for the purpose of supporting the sustainable working the sensor node, the control layer signals the hardware layer to lead the insufficient environmental energy to the preceding stabilizer and sparks the Li-ion battery to compensate it.

In the application layer, a TinyOS program samples the present output voltage of solar panel, the voltage of Li-ion battery and other useful information, such as the illumination intensity, temperature and humidity. They all serve as important parameters for the control layer. And this application runs on its own schedule provided by control layer according to the residual energy budget.

5.2. Hardware design

Fig. 6a shows a generic system architecture block of our implementation. The EFCon is an add-on circuit board,



(a) System Block (b) EFCon Platform

Fig. 6. EFCon hardware design.

whose size is only 66 mm × 32 mm. It bridges solar panel, Li-ion battery, and external TelosB node together. The circuit consists of two switches and an intelligent power circuit with two DC/DC converters for stabilizing the power of external node. The corresponding printed circuit board is shown in Fig. 6b. Due to the space limitation, we only explain a few features of the EFCon design in the rest of the section.

5.2.1. Control switches

In traditional solutions, solar panel and energy storage device, e.g. Li-ion battery, are connected through a diode [17], which is used to lead the current direction and prevent the backflows. Unfortunately, the typical forward voltage drop of a diode is 0.5 V, which means the solar panel's output voltage V_{solar} must be 0.5 V higher than that of the battery V_{bat}. If the voltage of the power supplied by the solar panel is not high enough, even if it is relatively high, the diode will still disconnect the solar panel from the battery, resulting in a waste of energy. Consequently, the entire network may fail for a certain period of time.

The first contribution of this prototype is replacing diode with a switch that is composed of a pair of triodes: a PNP and a NPN, as shown in Fig. 7. The typical forward voltage drop of a diode is 0.5 V, in other words, slight energy will be wasted in this diode. Alternatively, we use the PNP to connect the solar panel and the secondary DC/DC converter, with the emitter PNP connected to the former and the collector of PNP connected to the latter. The base of the PNP is connected to the collector of a NPN by a 4.7 kΩ resister. The emitter of the NPN is connected to the ground and the base of the NPN is connected to the GPIO port of the TelosB node. The external TelosB node controls the switch through its GPIO pin. Because the forward drop voltage between the collector and emitter of the triode is nearly 0 when the triode saturates, the TelosB sensor node can control the patterns of energy flow with little additional energy cost.

As shown in Fig. 6a, there are two switches in this circuit board. The coordination of these two switches can lead the current direction according to the four energy flow patterns. In *FF* and *DF* patterns, the switch 1 will be ON and the switch 2 will be OFF. When both switch 1 and switch 2 are ON, the *CF* pattern is activated. In *BF* pattern, the switch 1 will be OFF and the switch 2 will be ON.

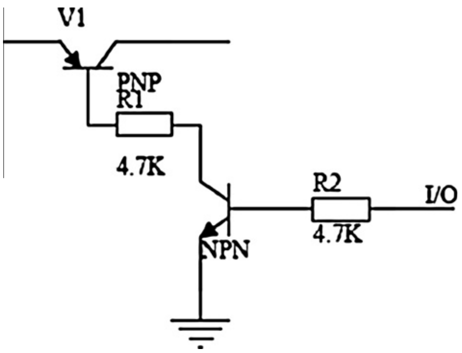


Fig. 7. Control switch.

5.2.2. Intelligent power circuit

In order to harvest the fluctuating ambient energy even under bad weather, the supplying voltage should be stabilized. On the other hand, the open voltage of Li-ion battery, ranging from 2.7 V to 4.2 V, should be stabilized into an output voltage of 3.3 V, which is typical for sensor node. In our prototype, we propose a novel solution of dual-converters for providing stable power according to different energy flows.

Because of the energy fluctuation, we choose an efficient step-up DC/DC converter (TPS61220 from TI, as shown in Fig. 8) as the proceeding converter, which connects the solar panel and terminal output. Normally a DC/DC converter draws energy and obtains working power from the energy source directly, assuming enough energy can be supplied by it. We change the typical circuit of TPS61220 by separating the input of L and VIN pin because of the unique feature of our prototype. The basic idea is that, although the startup voltage of this IC is extremely low, in some cloudy weather, the power harvested by the solar panel cannot provide enough power to the components and be generated to a higher voltage power. Thus we connect the L pin to the solar panel through an inductor, and the VIN pin to the Li-ion battery to guarantee working power. Therefore, even with a low environmental energy supply, this converter can still work. This converter is triggered in the *CF* pattern, and is controlled by the TelosB node.

A buck-boost DC/DC converter is placed as the terminal converter. It is used to stabilize the massive varying voltage from both Li-ion battery and solar panel to sensor working voltage.

5.2.3. External sensor node

Some other system, like TwinStar, supports two external sensor nodes: a working node and an optional companion node [7]. The two nodes are powered separately, with the working node powered by a ultra-capacitor, and the companion node powered by an additional battery. This design prevents the companion node's interfering with the working node [7]. However, such design will introduce extra hardware cost moderately.

In our EFCon platform, one TelosB node is attached to our system, as the unique working node. This node is powered by both the environmental energy and Li-ion battery. Besides the data sampling, processing, and wireless communication, the special capabilities of the TelosB in EFCon are as follows:

- Sampling the voltage of the Li-ion battery periodically.
- Sampling the output voltage of solar panel periodically.
- Controlling the energy flow direction by GPIO port on TelosB.
- Controlling the energy flow rate by dynamically adjusting duty cycle, sampling rate, and executing data aggregation.

The one-node design may increase the software burden constantly. Because of the energy constraint during the startup phase, we initially charge the Li-ion battery to its full capacity. At this time, the secondary converter will be driven directly by the Li-ion battery, and the TelosB node will be triggered. Once the sensor node starts working, the following strategy can be conducted consequently.

5.3. Software design

Our software is based on TinyOS 2.1, which is a widely used component-based operating system for WSNs, and the size of our program is less than 35 kB. We introduce two GPIO ports to control the two switches on the circuit board respectively, and two ADC12 ports to monitor the energy condition of both environment and battery. The luminous intensity is sampled through light sensor on TelosB node.

At the very beginning, we sample the necessary information, such as environmental energy, battery energy, and luminous intensity. Then, we compare the two energy levels and the luminous intensity, the energy flow pattern will be decided subsequently. The TinyOS program will trigger relevant electronic signal to control two switches toggling between ON and OFF.

On the other hand, the program running consumes slight energy. Therefore, the control process will be accomplished within a short time, and follow a fixed energy flow control strategy. For example, the luminous intensity will be sampled occasionally because the luminous intensity of daytime or night rarely changes.

6. Evaluation

To evaluate the performance of the proposed EFCon system, we implement a real testbed, as shown in Fig. 9. The system consists of 10 sensor nodes powered with EFCon system. Based on this testbed, the performance of EFCon system under different weather conditions is tested. Furthermore, a long-term experiment is conducted over one month from the early June to July in Hangzhou, China. The experimental results show that the EFCon system performs pretty well for real applications.

6.1. Charging and discharging measurement

Firstly, we test the charging and discharging pattern of our system under different scenarios. The charging

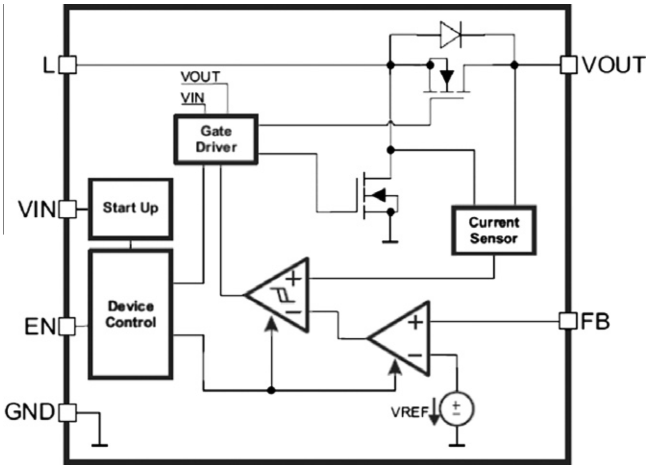


Fig. 8. Function block diagram of TPS61220.

Fig. 9. EFCon testbed.

experiment is conducted outdoor with moderate sunshine. As shown in Fig. 10a, the charging pattern is presented as the voltage vs. luminous intensity. We only present the pattern of one typical sensor node here because of limited space. The experimental results show that the charging procedure consists of two stages, which is determined by the chemical feature of the Li-ion battery. From the very beginning, the Li-ion battery is charged with a high current, when its voltage increasing rapidly. After the time that the voltage almost reaches its full capacity, the charging current will decrease to an extremely low level until its capacity is full.

We also test the discharging pattern under the circumstance without any environmental energy to be harvested. The duty cycle of the sensor node is set to 10% with all LEDs on. Fig. 10b show the voltage curve when discharging of the Li-ion battery with capacity of 1700 mAh. The voltage of the Li-ion battery declines moderately as providing energy to the external sensor node at the first few hours. When its energy is nearly exhausted, it stages a dramatically drop before the protection circuit working automatically when the voltage reaches to approximately 2.7 V.

6.2. Short-term experiment

As mentioned before, the energy flow has four patterns: *FF*, *DF*, *BF*, and *CF*. To evaluate the short-term performance of the proposed EFCon system, an experimental sensor network is deployed on the roof of a teaching building for 4 days. The duty cycle is set to 5% for each sensor node.

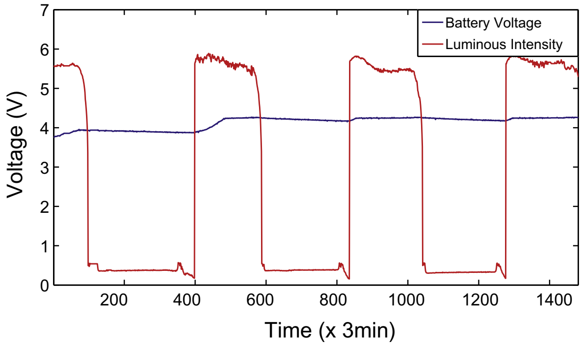


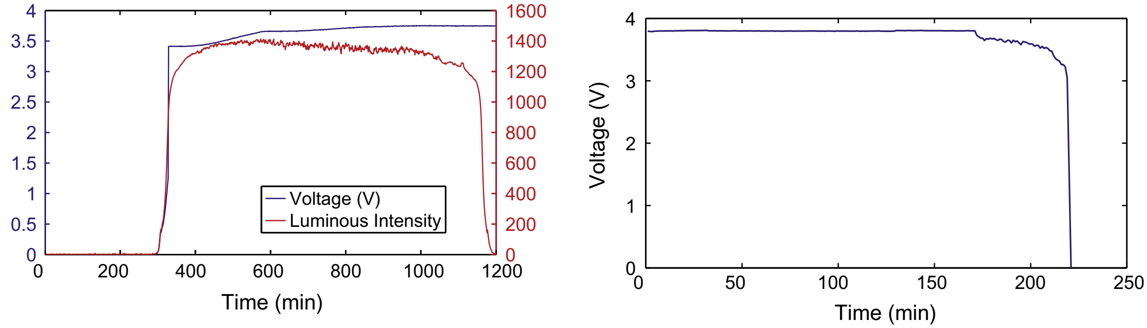
Fig. 11. Short-term experiment.

The experimental results are shown in Fig. 11. The energy of Li-ion battery is almost in its full capacity, with the voltage fluctuating around 4 V. In the second day, the sun is shining brightly and EFCon enters its *FF* pattern. As a result, the energy is charged to about 4.2 V, which is the highest nominal value of Li-ion battery. In the afternoon, EFCon turns to its *DF* pattern, and the energy in the Li-ion battery starts to power the external TelosB node when the sunshine decreases. In the following 2 days, the weather promotes the system stays in *DF* pattern in the daytime, and the *BF* pattern at night.

The energy utilizing pattern is presented in Fig. 12. The two curves stand for the results of the sensor network with two different sampling rates under the same cloudy weather during 3 days. The sampling rate of the red curve is set to 50%, while that of the blue one is set to 10%. The experimental results show that the energy flow rate will be controlled by the sampling rate and the sensor node could experience a longer lifetime with a suitable sampling rate.

6.3. Long-term experiment

We took a long-term experiment over one month with the weather changing including cloudy, rainy and sunny and we have collected over 20,000 valid data in total. The system collect light luminous intensity and temperature



(a) The Charging Pattern Measured in Outdoor Environment

(b) The Discharging Pattern

Fig. 10. Charging and discharging pattern.

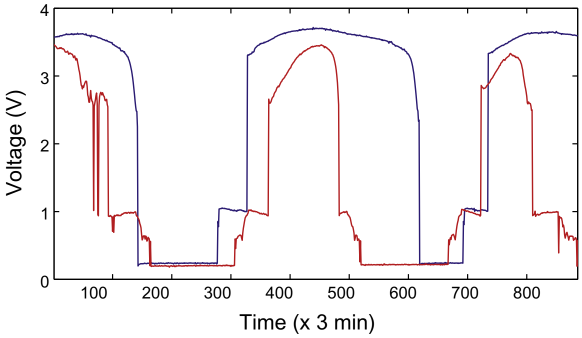


Fig. 12. Residual energy vs. sampling rate.

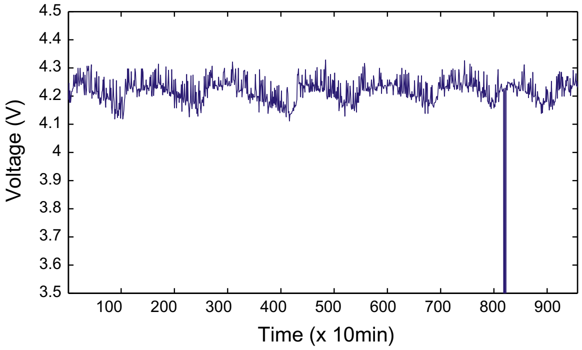


Fig. 13. Long-term experiment.

in the forest with 10% duty cycle. We intercept an piece of data across 8 days, which is shown in Fig. 13.

Experimental results show that the sensor network maintains sustainability over 30 days without interrupted by shortage of energy. The fact that the residual energy stays above a certain level has validated the energy flow control system. In the daytime, EFCon enters *FF* or *DF* patterns and the Li-ion battery is charged. While in the night, the EFCon turns into *BF* pattern, with the energy dropped continually. As shown in Fig. 13, in the seventh day, there is packet loss lasting for a while. Based on the energy flow control strategy, the residual energy in Li-ion battery stays around an optimistic level during the whole experiment period.

7. Conclusion

In this paper, we formulate the energy utilizing problem in WSNs as an energy flow control problem. We present an energy flow control system, called EFCon, which enables WSNs to work in a more sustainable way. We further propose an approach which is able to switch among four energy flow patterns automatically, and design a feasible solution to control the energy flow rate. The EFCon system is implemented with a novel circuit board and software and its performance is evaluated by both short-term and long-term experiments. Currently, we are working on a larger scale deployment to evaluate the network sustainability of WSNs.

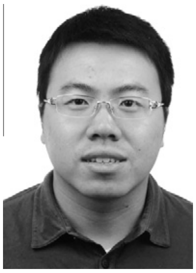
Acknowledgments

This paper is supported by the National Basic Research Program of China (973 Program) under Grant No. 2010CB334707, National Natural Science Foundation of China under Grant No. 60803126, 61003298 and 60903167, Zhejiang Provincial Natural Science Foundation under Grant No. Z1080979, the program for Zhejiang Provincial Key Innovative Research Team on Sensor Networks, the program for Zhejiang Provincial Overseas High-Level Talents (One-hundred Talents Program).

References

[1] L. Mo, Y. He, Y. Liu, J. Zhao, S.J. Tang, X.Y. Li, G. Dai, Canopy closure estimates with GreenOrbs: sustainable sensing in the forest, in: SenSys, ACM, 2009, pp. 99–112.
[2] X. Jiang, J. Polastre, D. Culler, Perpetual environmentally powered sensor networks, in: IPSN, IEEE Press, 2005, p. 65.
[3] J. Polastre, R. Szewczyk, D. Culler, Telos: enabling ultra-low power wireless research, in: IPSN, IEEE Press, 2005, p. 48.
[4] C. Park, P.H. Chou, Ambimax: autonomous energy harvesting platform for multi-supply wireless sensor nodes, SECON06 1 (2006) 168–177.
[5] S. Meninger, J.O. Mur-Miranda, R. Amirtharajah, A. Chandrakasan, J.H. Lang, C. Mit, Vibration-to-electric energy conversion, IEEE Transactions on Very Large Scale Integration (VLSI) Systems 9 (1) (2001) 64–76.
[6] I. Stark, Invited talk: thermal energy harvesting with Thermo Life, in: International Workshop on Wearable and Implantable Body Sensor Networks, BSN 2006, 2006, pp. 19–22.
[7] T. Zhu, Z. Zhong, Y. Gu, T. He, Z.L. Zhang, Leakage-aware energy synchronization for wireless sensor networks, in: MobiSys, ACM, 2009, pp. 319–332.
[8] P. Dutta, J. Hui, J. Jeong, S. Kim, C. Sharp, J. Taneja, G. Tolle, K. Whitehouse, D. Culler, Trio: enabling sustainable and scalable outdoor wireless sensor network deployments, in: IPSN, ACM, 2006, p. 415.
[9] C. Park, PH Chou, Power utility maximization for multiple-supply systems by a load-matching switch, in: Proceedings of the 2004 International Symposium on Low Power Electronics and Design, 2004. ISLPED'04, 2004, pp. 168–173.
[10] V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, M. Srivastava, Design considerations for solar energy harvesting wireless embedded systems, in: IPSN, 2005, pp. 457–462.
[11] K. Lin, J. Yu, J. Hsu, S. Zahedi, D. Lee, J. Friedman, A. Kansal, V. Raghunathan, M. Srivastava, Heliomote: enabling long-lived sensor networks through solar energy harvesting, in: SenSys, ACM, 2005, p. 309.
[12] A. Kansal, J. Hsu, S. Zahedi, M.B. Srivastava, Power management in energy harvesting sensor networks, ACM TECS 6 (4) (2007) 32.
[13] Y. Yang, L. Wang, D.K. Noh, H.K. Le, T.F. Abdelzaher, Solarstore: enhancing data reliability in solar-powered storage-centric sensor networks, in: MobiSys, ACM, 2009, pp. 333–346.
[14] C. Moser, J.J. Chen, L. Thiele, Power management in energy harvesting embedded systems with discrete service levels, in: Proceedings of the 14th ACM/IEEE International Symposium on Low Power Electronics and Design, ACM, 2009, pp. 413–418.
[15] X. Shen, C. Bo, J. Zhang, G. Dai, X. Mao, X.Y. Li, SolarMote: a low-cost solar energy supplying and monitoring system for wireless sensor networks, in: SenSys, ACM, 2009, pp. 413–414.
[16] L. Selavo, A. Wood, Q. Cao, T. Sookoor, H. Liu, A. Srinivasan, Y. Wu, W. Kang, J. Stankovic, D. Young, et al., Luster: wireless sensor network for environmental research, in: SenSys, ACM, 2007, p. 116.
[17] C. Alippi, C. Galperti, An adaptive system for optimal solar energy harvesting in wireless sensor network nodes, IEEE Transactions on Circuits and Systems I: Regular Papers 55 (6) (2008) 1742–1750.

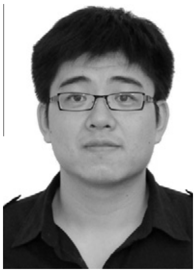
Xingfa Shen received his B.E. degree in Electrical Engineering and Ph.D. in Control Science and Engineering from Zhejiang University, China in 2000 and 2007. He is currently an Associate Professor at Hangzhou Dianzi University. His research interests include wireless sensor networks, embedded systems, etc.



Cheng Bo received his B.E. degree in Computer Science from Hangzhou Dianzi University, China in 2007. He is currently master student at Hangzhou Dianzi University. His research interests include wireless sensor networks, hardware design.

Jianhui Zhang received his B.S. degree in Mechanotronics and M.S. degree in Fluid Mechanics from Northwestern Polytechnical University, China, in 2000 and 2003. He received his Ph.D. degree in Control Theory and Engineering from Zhejiang University, China, in 2008. He is currently an Assistant Professor at Hangzhou Dianzi University. His research interests include algorithm design, wireless networks, etc.

Shaojie Tang is a Computer Science PhD student at Illinois Institute of Technology. He received B.S. at Radio Engineering, Southeast University, PR China, 2006. His research field is on algorithm design, optimization, security of wireless networks, electronic commerce as well as online social network. He is a student member of IEEE.



Xufei Mao is a Computer Science Ph.D. student at Illinois Institute of Technology. He received B.S. from Shenyang Univ. of Tech. and M.S. from Northeastern University, China. His research interests include design and analysis of algorithms concerning wireless networks, network security, etc.

Guojun Dai received his Ph.D. degree in Electrical Engineering from Zhejiang University, China, in 1998. He is currently a Professor at Hangzhou Dianzi University. His research interests include embeded systems, electrical control, etc.